COLLATION AND SYNTHESIS OF HYDRAULIC INFORMATION FROM ENVIRONMENTAL FLOW REQUIREMENT STUDIES

Report to the
Water Research Commission

by

AL Birkhead & AY Desai
Streamflow Solutions CC

WRC Report No. KV 291/11
ISBN 978-1-4312-0186-0

January 2011

The publication of this report emanates from WRC consultancy titled Synthesis *of hydraulic information collected over the past decade in southern Africa to inform Environmental Flow Requirements* (WRC Project No. K8/795).

DISCLAIMER

ACKNOWLEDGEMENTS

The following contributions are gratefully acknowledged -

Dr Mandy Uys (Laughing Waters) for collating data.

Delana Louw (Rivers for Africa) for providing site-related information.

Dr Angelina Jordanova (Golder Associates) for providing hydraulic information.

Dr Cate Brown (Southern Waters Ecological Research and Consulting) for providing reports from previous studies.

The Komati Basin Water Authority (KOBWA) for providing data from the Komati River (South Africa and Swaziland).

The Snowy Mountain Engineering Corporation (SMEC) for allowing use of data from a site on the Phuthiatsane River in Lesotho.

TABLE OF CONTENTS

LIST OF FIGURES

ABBREVIATIONS AND ACRONYMS

AMSL	Above Mean Sea Level
C	Comprehensive Level of Reserve
DB	Data-Base
DRC	Democratic Republic of the Congo
DType	Dominant sediment type
DWA	Department of Water Affairs
*d*x	sediment diameter for which x % is finer
EFR	Environmental Flow Requirement
GUnit	Geomorphological Unit
GZone	Geomorphological Zone
HP	Hydropower Project
I	Intermediate Level of Reserve
ID	identity
LES	Lesotho
MOZ	Mozambique
n	Manning's flow resistance coefficient
n(X-X)	*n* between cross-sections
na	not applicable
NMAR	Natural Mean Annual Runoff
Nr	Number
PES	Present Ecological Category
PMAR	Present-day Mean Annual Runoff
Pt. ID	point number (= row number in data-base)
Q <	lowest discharge to which rating function applies
< Q <	discharge between rating functions
< Q <, < Q	highest discharge to which rating function applies
R3	Rapid Level III Reserve
Rel. y	maximum flow depth relative to sediment size
Rel. yav	average flow depth relative to sediment size
ResLev	Ecological Reserve Level
Runoff	Mean Annual Runoff
SA	South Africa
SedType	Sediment Type
SWAZI	Swaziland
VS	Valley or topographical (1:50 000 map) slope
WRC	Water Research Commission
X	Cross-section

1 INTRODUCTION

1.1 BACKGROUND

Large quantities of river hydraulic information have been collected over the past decade in the course of undertaking Environmental Flow Requirement (EFR) assessments (including Instream Flow Requirements), and more recently, Ecological Reserve studies. The clients involved have been mainly the Department of Water Affairs (South Africa), as well as private organisations and government departments in neighbouring countries (*e.g.* Swaziland, Lesotho and Mozambique). These data are in electronic format and hardcopies in the form of project reports, electronic files (workbook data), and total approximately 46 projects, 218 sites and 821 cross-sections.

The data reside largely with the people contracted to undertake the work[1]. Ongoing involvement has resulted in these individuals having gained considerable experience in the field of hydraulic applications for assessing environmental flow requirements for rivers. Personal experience, however, is not transferable. For this reason, a means of transferring the hydraulic information through analysis of existing data and results will be most beneficial to future EFRs, and therefore, water resource planning in southern Africa.

Kleynhans *et al*. (2008) discuss the principles of a process to estimate and/or extrapolate Environmental Flow Requirements. The estimation component requires the prediction, at the desktop level, of the (ecologically relevant) low flow inundated channel width.

A (current) Water Research Commission (WRC) project (K5/1856), entitled, "Development of a revised desktop Reserve estimation model" requires the development of a hydraulics sub-model for estimating hydraulic habitat. The product of the study reported here is useful for the development of this sub-model, since it requires the generation of "characteristic hydraulic information". This information, together with ecological components, (presently being developed) should allow EFRs to be predicted at the desktop level - *i.e.* without field data collection, but with a "reasonable" degree of certainty.

1.2 OBJECTIVES

The objectives of this project have been to -

- collate available hydraulic and relevant site-related information from previous (mainly) EFR studies, and
- determine whether the data display empirical relationships.

[1] Mainly Birkhead and Jordanova, although the DWA has also carried out hydraulics studies - primarily for Rapid Level III determinations (refer to Birkhead, 2010).

The primary product of this project is a data-base of hydraulic and related information, as well as a means for synthesising these data to provide graphical output. This report is therefore a brief description of the data-base and methods for analysing the information.
The project deliverables, as given in the study proposal, include -

- a data-base (in spreadsheet format) of hydraulic and related information for EFR sites with appropriate hydraulic characteristics (*e.g.* not pools which are not resistance controlled - all geomorphic units are actually included in the data-base for completeness),
- graphical representations of the relationships between determinants, and
- mathematical relationships between parameters - where reasonable relationships exist.

2 HYDRAULIC DATA-BASE AND DATA SYNTHESIS

2.1 EFR HYDRAULICS DB V310809.XLS

The EFR hydraulics data-base (DB) and analysis routines are contained in the Workbook EFR Hydraulic DB v310809.xls, which is the main product of this study. The components of this are briefly described in the following sections.

2.1.1 Worksheet 1 - About this project

This first sheet provides a brief background to the project, the reference to this data-base, and supporting documentation (including this report).

2.1.2 Worksheet 2 - Hydraulics DB

The second sheet is the hydraulics DB - refer to Figure 2.1. The DB consists of columns of parameters and rows where the data are entered.

The parameters (arranged in columns) include -

- Project and/or River name
- River name
- Quaternary catchment
- Site
    - Name
    - Number (Nr)
    - Cross-section Number (X Nr)
- Date (of data collection)
- Comment

- <u>Runoff (10^6 m^3/annum), including</u>
    - Natural (NMAR)
    - Present-day (PMAR)

- <u>Site location information, including -</u>
    - Latitude (decimal degrees S)
    - Longitude (decimal degrees E)
    - Altitude (AMSL)

- <u>Biophysical information, including -</u>
    - Present Ecological Status (PES)
    - Reserve determination level (Rapid III, Intermediate or Comprehensive) (ResLev)
    - Ecological Region
    - Geomorphological Zone: A - E (GZone)
    - Geomorphological Units (characterised by the cross-section)
    - Geomorphological Unit - Dominant (GUnit)
    - Sediment types and/or sizes, including -
        - Types (Sand, Grav(el), Cob(ble), Bould(er) or Bed(rock)
        - Dominant Type (one of the above) (SedType)
        - *d*16, *d*50 & *d*84 sizes

- <u>Hydraulic data (per rating measurement), including -</u>
    - Discharge, Q (m^3/s)
    - Maximum flow depth, y (m)
    - Average flow depth, *yav* (m)
    - Cross-sectional flow area, A (m^2)
    - Inundated width, W (m)
    - Wetted perimeter, P (m)
    - Average velocity, V (m/s)
    - Comment/s
    - Inundated width (W) for maximum flow depths (y) of
        - 0.10, 0.20 and 0.30 m
    - Water surface slope, S (m/m)
    - Valley slope, *VS* (topographical map or similar)
    - Manning's flow resistance
        - coefficient (n)
        - between (X-X) or at cross-sections (blank)

- <u>Hydraulic data (per rating measurement), including -</u>
    - a, b and c (maximum of three curves permitted)
    - ranges of applicability of the relationships (in terms of discharge)

The data (arranged in rows) are according to -

- Intermediate/Comprehensive or Rapid Level III Reserve determinations
    - Project name
        - River name
            - Site name and number
                - ✓ Cross-section designation (A, B, C, *etc.*)

Data related to the site (including, quaternary catchment, site name and number, runoff, site location, PES, Reserve determination level, ecological region and geomorphological zone) are only entered on the first row pertaining to that site; data related to the cross-section (geomorphological unit/s, sediment types and/or sizes, inundated widths for the three given flow depths, valley slope and the rating relationship) are only entered on the first row pertaining to each cross-section; the remaining hydraulic data are entered on subsequent rows for each measured discharge and associated date of measurement. In this way, manual data entry is kept to a minimum.

The current DB consists of 57 columns and 1180 rows. To assist with data entry and worksheet navigation, columns and rows have been grouped according to parameters and data, respectively. These are indicated in the above lists by underlining (*i.e*. for columns - runoff, site location, biophysical information, hydraulic information and (modelled) ratings, and for rows - Reserve level and project name). To expand/contract the grouping, click on the "+/-" buttons in the top and left margins, respectively.

2.1.3 Worksheet 3 - Abbreviations & DB Key

The third worksheet in the workbook provides lists of abbreviations and acronyms used in the DB, as well as a key to certain shaded cells.

2.1.4 Worksheet 4 - Filter, plot & curve fit

The final and fourth sheet in the workbook allows the user to plot data according to user-defined filters, and to undertake a non-linear regression analysis (Figure 2.2). A maximum of three series may be plotted - with each using the same parameters. Each of the series data may be filtered using different parameters and data range values (filtering a plotted parameter only changes the scale of the relevant axis). Data entry is only in grey-shaded cells.

Parameters available for plotting on the X-axis include - *NMAR*, *PMAR*, *Q, y, yav, W, P, A, V, S VS,* and *n*, and Y-axis parameters include these and additionally *W*(*y*). These parameters are selected from drop-down menu lists. Also, the plotted data points may be labelled according to - GZone, GUnit, SedType, NMAR, *y, yav, W, P, V, S VS,* and *n.* EXCEL, however, only allows for data-point labelling according to the X- or Y-axes data values, and an Add-In is therefore required for labelling with user-defined values. These are available as freeware for download from the internet (*e.g.* XY Chart Labeler Version 7.0.11. at www.appspro.com).

Data points are also given ID's, and the row number in the DB is used. This allows any data point to be cross-referenced back to its entry in the DB. By holding the cursor over a plotted data point, the X- and Y- axes values are displayed. The X-axis parameter value may be looked-up in the series listing, which for this purpose is in ascending order.

For each of the series, lists of available parameters for filtering are included. Filtering options are also selected from drop-down menu lists, where appropriate. The parameters available for filtering the data include both descriptive parameters: ResLev, GZone, GUnit, SedType, *n*(X-X), and numeric parameters: *NMAR*, *PMAR*, *Q, y, yav, W, P, V, S VS, n*, and *c1* (where *c1* is the modelled depth at the cessation of flow). For the descriptive parameters, drop-down menus allow the selection of either "All" (*i.e.* no filtering) or relevant labels as entered in the DB. For numerically defined parameters, "All" or "Range" may be selected. For "Range", the user is required to enter the minimum and maximum numeric values in adjacent columns of the table. Finally, regarding the filtering, each or all series data may be plotted by making the appropriate selection.

The option for non-linear (power function) curve fitting and plotting is also included on Worksheet 4. The relationship used is a power function of the form: $Y = aX^b + c$, where the constant term, *c*, may be specified as zero (refer to Figure 2.2). Other (differentiable) functions may be included in the software with future versions, depending on the form of relationships that develop with further necessary work (refer to Section 2.3). The computation proceeds from either "starting" or "fitted" initial values for the regression coefficients - refer to Section 2.2.3.

2.2 FILTERING, PLOTTING AND NON-LINEAR REGRESSION ANALYSIS

It was initially envisaged that standard routines available in EXCEL (*e.g.* filtering) would be used to synthesize the data. However, it became obvious that such procedures are not suited to the type of multi-criteria analyses required. It was therefore necessary to write suitable software for -

- loading the DB to array memory,
- parameter filtering and data plotting, and
- non-linear regression analysis.

These procedures require the running of EXCEL Macros (or Visual Basic code). In order to run (unsigned - such as these) macros in EXCEL, the security level must be set to Medium - Low is not recommended as it may allow macros (which may be malicious) to be automatically executed. To change macro security, go to Tools/Options/Security/Macro Security. If the workbook was opened prior to requiring a change in the security level, then close and re-open the workbook to apply the changed security level to this workbook. Enable macros on (re-)opening.

To facilitate the running of the software, a ‘Run’ drop-down menu is automatically added to the Command Bar (before the Help menu) on workbook activation - *i.e.* when the workbook is opened. This menu control will therefore not appear if macros are Disabled - either by the user or a high security level setting.

Alternatively, the coding may be executed by selecting "Tools>Macro>Macros" from the Command Bar, and then selecting the appropriate software to execute.

2.2.1 Loading the DB and completing entries

To undertake the analysis, it is necessary to first load the DB entries to array memory, by selecting "Run>Load data-base". This also fills-in the null entries from the DB worksheet, by inserting, for example, project, river and site names, cross-section designations, *etc*. for each hydraulic data entry. This is necessary for the ensuing analysis.

2.2.2 Parameter filtering and data plotting

To perform the data filtering and plotting, select "Run>Filter and plot" from the drop down menu on the Command Bar. The graphical display is updated according to the selected X- and Y-axis parameters and data filtering options.

2.2.3 Non-linear regression

EXCEL incorporates a very basic linear regression analysis, whereas a non-linear analysis is generally more appropriate in this application. Although (freeware) software is also available from the internet for this purpose, suitable interfacing is generally not provided, and the data is required to be exported to file or even entered manually. For this reason, a non-linear regression analysis is included as part of the analysis software.

The unconstrained optimisation procedure of Fletcher and Reeves (1964) for arbitrary differentiable functions has been used to compute the coefficients that minimise the sum of the squares of the error. The computational procedure is iterative (due to non-linearity), proceeding from starting (or initial) values for the regression coefficients (a, b & c). The maximum number of iterations is hard-coded to 1000. To ensure convergence, the analysis may be repeated, starting with "fitted" values from a previous computation.

2.2.4 Error handling

The data filtering and regression routines have been written with minimal error trapping and handling capabilities, since the product is intended to facilitate the research and is not for commercial purposes. Cell validation (including data selection from drop-down menu lists) has been used, wherever possible, to prevent incorrect data entry.

To make the routines more robust, further error trapping and handling may be included in further version of the routines.

2.3 EXAMPLE PLOTS AND FITTED RELATIONSHIPS

Four example plots are provided in Figure 2.3 to Figure 2.6.

The first plot (Figure 2.3) is between maximum and average flow depths - the relationship found to be most significant (R^2 = 0.91).

The second plot is inundated width (for an ecologically relevant low-flow depth) against mean annual runoff (Figure 2.4). The need to predict inundated width for flow estimation methods is discussed by Birkhead (2008). Although substantial scatter is displayed, reasonably coarse estimates of width may be adequate for certain situations such as for predicting site similarity for ecological purposes (refer to Kleynhans, 2008).

Flow resistance is fundamental to hydraulic analyses, and Manning's flow resistance coefficient is plotted against average depth in Figure 2.5. Both series show substantial scatter and no significant relationship is plotted. This is somewhat expected, given the large resistance elements characteristic of EFR sites.

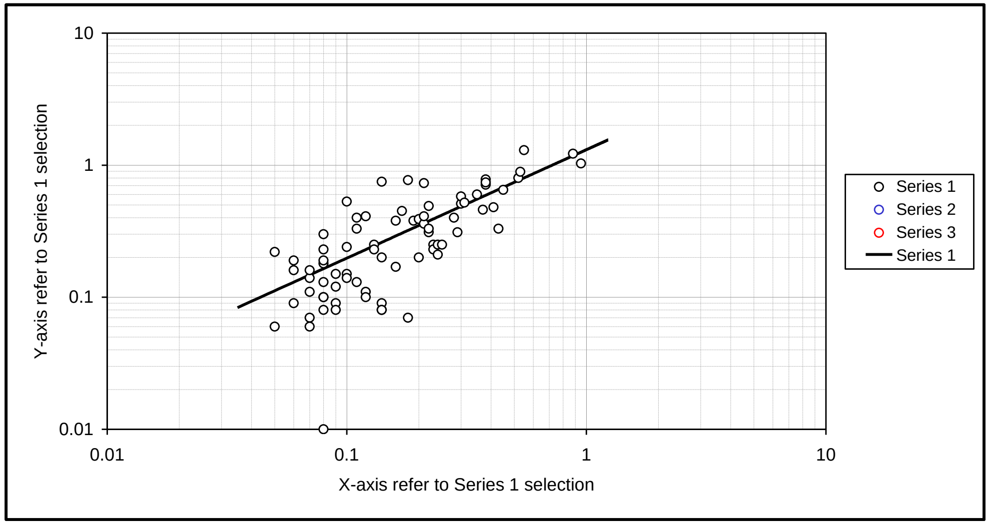
The final plot (Figure 2.6) is of average velocity against average depth, which although only moderately correlated (R^2= 0.68), is encouraging. It is envisaged that further data and analyses will improve the correlations, by incorporating additional parameters (mainly relative flow depth and the density of dominant bed substrates), coupled with multivariate analyses directed largely by the work of Jordanova and James (2007).

Project and/or River	River	Quaternary catchment	Site			Date	Comment	Runoff	Natural (Mm^3)	Present day (Mm^3)	Site Location	Biophysical Info	Hydraulic Data	Rating Parameters
			Name	Nr	X Nr									
Intermediate & Comprehensive														
Rapid Level III														
Erasmuskloof														
Reserve Estimation														
Komati														
Crocodile														
Sabie														
	Sabane	X31D	Sabane	6	A (Straight)	2008-06-11			19.24	4.74				
					A (Bent)	2008-06-11								
	Motlagomatsana	X32B	Motlagomatsana	7	A	2008-06-12			0.31	0.29				
	Sekgamorago	X32A	Sekgamorago	8	A	2008-06-12			1.04	1.00				
	Lone Creek	X31A	Lone Creek	9	A	2008-06-13			11.15	8.54				
	Sabie	X31A	Sabie	10	A	2008-06-13			26.48	20.28				
Mokolo														
Upper Vaal														
Frikkie se Loop														
Ncandu														
Mhlatuze														
Mngeni														
Modder/Riet														
Murara/Mutshindudi														
Pongola/Lusushawana/Mlomati														
Oudtshoorn														
Planning Estimate														
Sand														
Transkei														
Tsitsikama														
Ulundi (DRC)														
Umhlatuzana														
Vaal														
Zaaihoek														

END OF DATA

Figure 2.1 Select cells showing the partial hydraulics DB sheet, with rows and runoff data expanded for the Sabie River and Reserve Estimation projects.

FILTER DATA, PLOT SERIES & FIT RELATIONSHIP



Filter Series

Variable	Series 1			Series 2			Series 3		
	Select from list	For 'range' enter min. and max.		Select from list	For 'range' enter min. and max.		Select from list	For 'range' enter min. and max.	
		>=	<=		>=	<=		>=	<=
ResLev	All			All			All		
GZone	All			All			All		
GUnit	Riffle			Rapid			Run		
SedType	All			All			All		
n (X-X)	Exclude			Include			Include		
NMAR	All			All			All		
PMAR	All			All			All		
Q	All			All			All		
y	All	0.01	10	All	0.01	10	All	0.01	10
yav	All	0.01	10	All	0.01	10	All	0.01	10
P	All			All			All		
W	All			All			All		
V	All			All			All		
S	Range	0.005	1	Range	0.005	1	All		
VS	All			All			All		
n	All	0	1	Range	0	1	Range	0	1
c1	Range	0	0	Range	0	0	Range	0	0
W (*y*)	W(0.3)			W(0.1)			W(0.2)		
Rel. y	For future use								
Rel. yav									
Plot	yes			no			no		

Plot Series

Series 1				Series 2				Series 3			
Pt. ID	X-axis	Y-axis	Label	Pt. ID	X-axis	Y-axis	Label	Pt. ID	X-axis	Y-axis	Label
	yav	V	None								
1085	0.05	0.22									
247	0.05	0.06									
1138	0.06	0.16									
1051	0.06	0.09									
1164	0.06	0.19									
1086	0.07	0.07									
236	0.07	0.06									
246	0.07	0.11									

Regression ($y = ax^b + c$)

Series 1				
Variable	Start	Fitted	X-axis	Y-axis
a	1	1.31	0.035	0.08353
b	1	0.821	0.0374	0.08821
c	1	0	0.0398	0.09283
R^2		0.677	0.0422	0.0974
Start	Fitted		0.0446	0.10193
Fit c	no		0.047	0.10641
Plot	yes		0.0494	0.11085
			0.0518	0.11525

Figure 2.2 Layout of the data filtering, plotting and curve fitting sheet

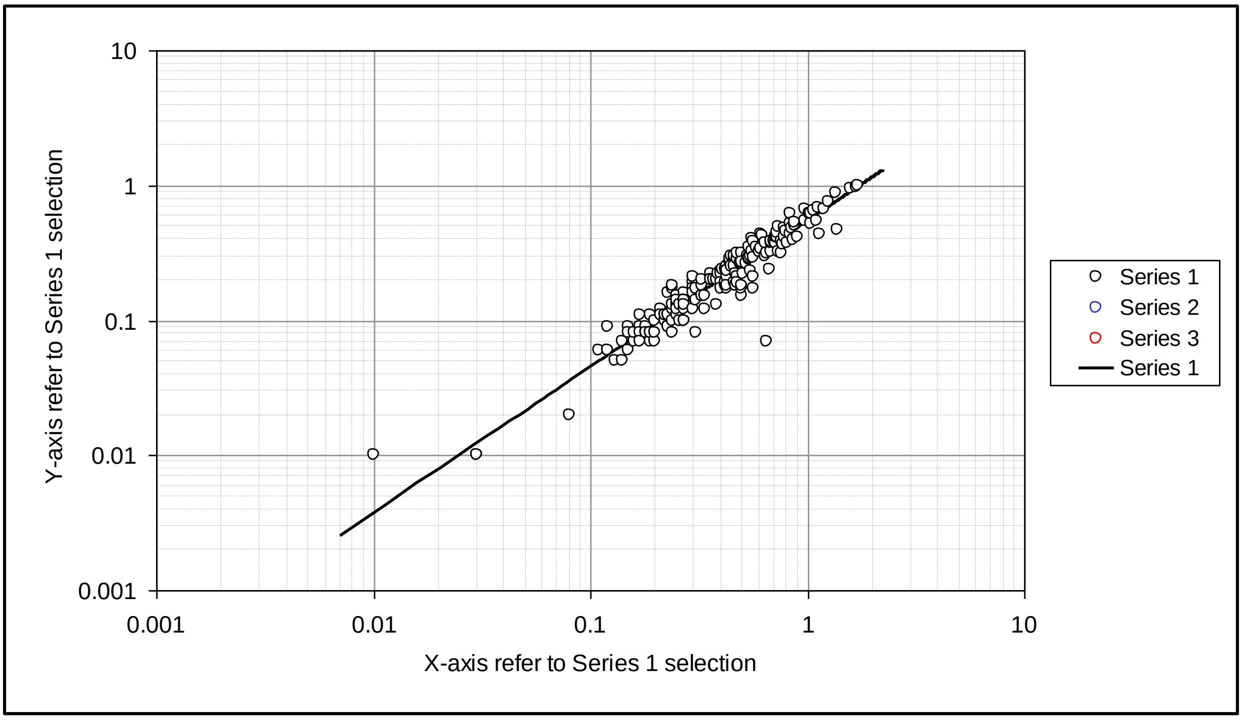


Figure 2.3 **Plot of average flow depth (*yav*) (Y-axis) against maximum flow depth (*y*) (X-axis). The data are filtered for (1) water surface slopes (*S*) greater than 0.005 (generally riffles, rapids and geomorphic units with high local water surface slopes), and (2) for cross-sections with zero (modelled) residual flow depth (*i.e.* excludes pools). The regression equation given by $yav = 0.55y^{1.08}$ is also plotted (R^2 = 0.91).**

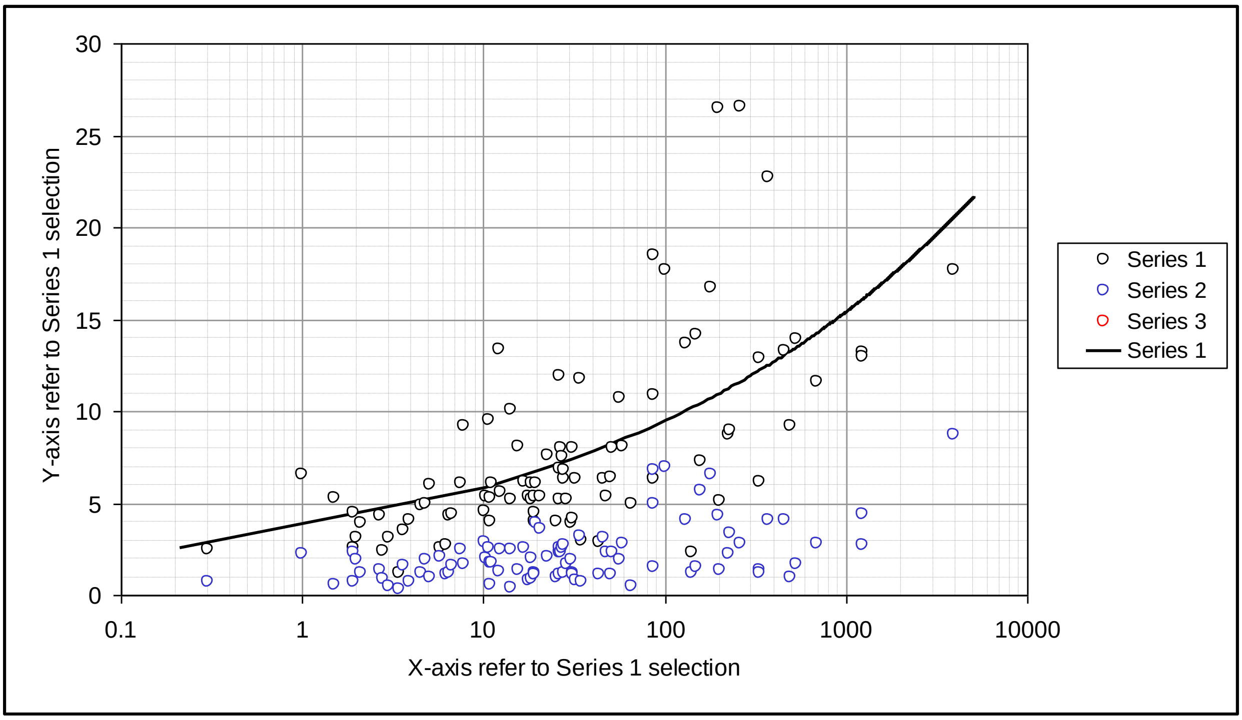


Figure 2.4 **Plot of inundated channel width (Y-axis) against Natural Mean Annual Runoff (*NMAR*) (X-axis) for depths of 0.30 m (Series 1) and 0.10 (Series 2). The data are filtered for (1) water surface slopes (*S*) greater than 0.005 (generally riffles, rapids and geomorphic units with high local water surface slopes), and (2) for cross-sections with zero (modelled) residual flow depth (*i.e.* excludes pools). The regression equation given by $W(0.3) = 3.59NMAR^{0.211}$ is also plotted (Series 1).**

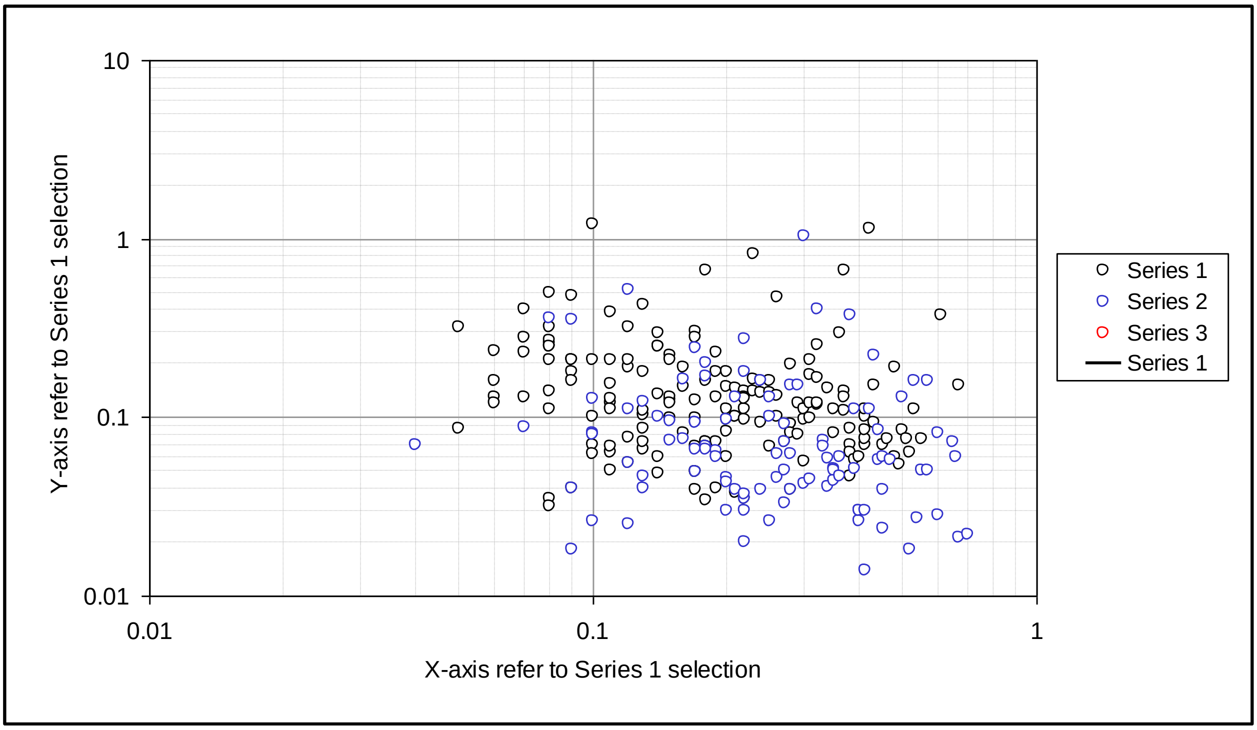


Figure 2.5 Plot of flow resistance (*n*) against average flow depth (*yav*). Series 1 is for water surface slopes (*S*) greater than 0.005 (generally riffles, rapids and geomorphic units with high local water surface slopes), and Series 2 is for slopes less than 0.005 (generally runs). The data are also filtered for cross-sections with zero (modelled) residual flow depth (*i.e.* excludes pools). No significant relationships are evident.

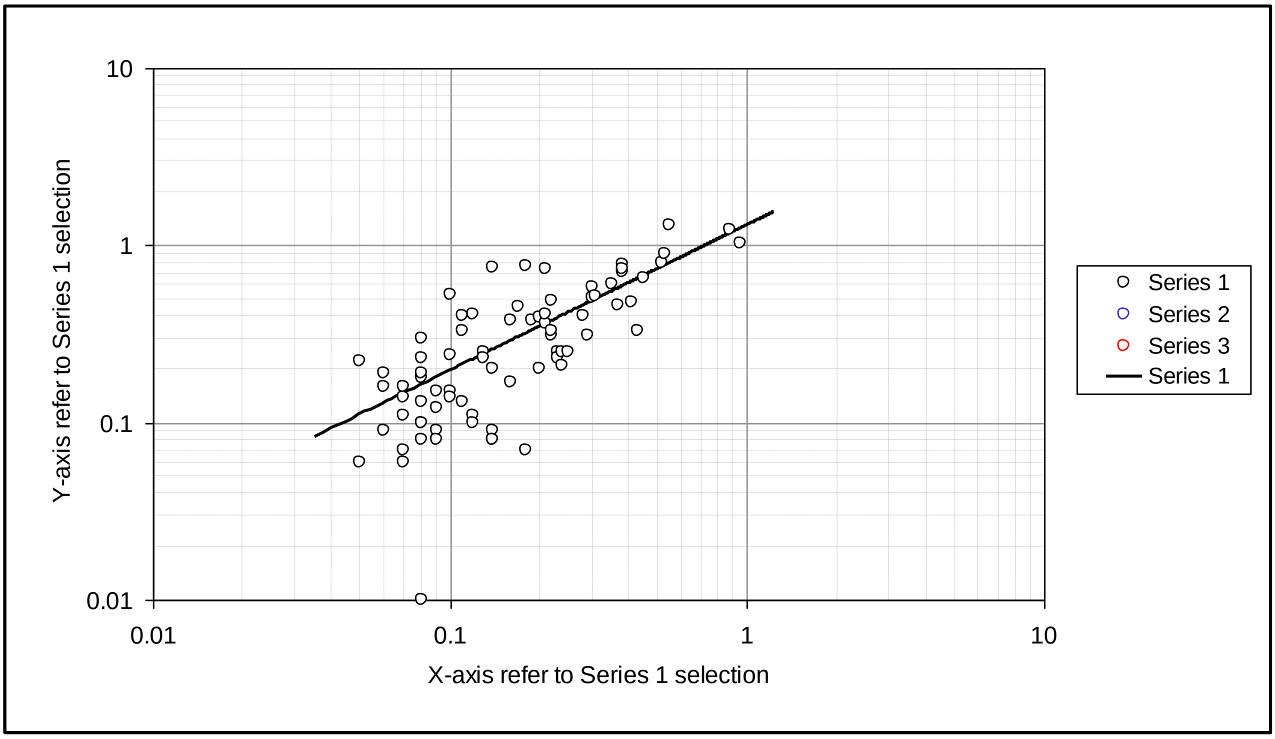


Figure 2.6 Plot of average flow velocity (*V*) against average flow depth (*yav*). The data are filtered for (1) water surface slopes (*S*) greater than 0.005 (generally riffles, rapids and geomorphic units with high local water surface slopes), and (2) for cross-sections with zero (modelled) residual flow depth. (*i.e.* zero depth at the cessation of flow). The relationship is given by $V = 1.31 yav^{0.621}$ ($R^2 = 0.68$).

3 REFERENCES

Birkhead, A.L., 2008. Chapter 3: Developing an approach for EWR estimation using biotic presence, flow preferences and availability of hydraulic habitat. In: Kleynhans *et al*., 2008. Principles of a process to estimate and/or extrapolate Environmental Flow Requirements. Water Research Commission Report No. KV 210/8.

Birkhead, A.L. in 2010. The role of Ecohydraulics in the South African Ecological Reserve. In: Ecohydraulics for South African Rivers, James, C.S. and King, J.M. (eds), Water Research Commission Project no. K5/1767/1, Pretoria, South Africa.

Fletcher, R., and Reeves, C.M., 1964. Function minimisation by conjugate gradients. Comput. J. 7, 149-154.

Jordanova, A.A. and James, C.S., 2007. Low flow hydraulics in rivers for Environmental applications. Water Research Commission Report No. 1405/1/07. 296 pp.

Kleynhans, C.J., 2008. Chapter 2: Developing an approach for assessing site similarity and predicting fish indicator species. In: Kleynhans *et al*., 2008. Principles of a process to estimate and/or extrapolate Environmental Flow Requirements. Water Research Commission Report No. KV 210/8.

Kleynhans, C.J., Birkhead, A.L. and Louw, M.D., 2008. Principles of a process to estimate and/or extrapolate Environmental Flow Requirements. Water Research Commission Report No. KV 210/8.